New ArF immersion light source introduces technologies for high-volume 14nm manufacturing and beyond

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ABSTRACT

Semiconductor market demand for improved performance at lower cost continues to drive enhancements in excimer light source technologies. Multi-patterning lithography solutions to extend deep-UV (DUV) immersion have driven requirements such as higher throughput and higher efficiencies to maximize the utilization of leading-edge lithography equipment. Three key light source parameters have direct influence on patterning performance – energy, wavelength and bandwidth stability – and they have been the primary areas of continuous improvement. With 14nm node development, a number of studies have shown the direct influence of bandwidth stability on CD uniformity for certain patterns and geometries, leading to the desire for further improvements in this area. More recent studies also examined the impact of bandwidth on 10nm logic node patterning [1]. Alongside these drivers, increasing cost per patterning layer continues to demand further improvements in operating costs and efficiencies from the lithography tools, and the light source can offer further gains in these areas as well. This paper introduces several light source technologies that are embodied in a next-generation light source, the Cymer XLR® 700ix, which is an extension of the ring laser architecture introduced 8 years ago. These technologies enable a significant improvement in bandwidth stability as well as notable reductions in operating costs through more efficient gas management algorithms and lower facilities costs.

1. INTRODUCTION

In 2007 Cymer introduced a ring-laser architecture light source, the XLR® 500i, as an extendible, ArF immersion platform to enable improvements in dose stability and cost-of-ownership [2]. Subsequent improvements included improvements in bandwidth control, wavelength control and higher power, to address higher throughput scanner requirements as well as tighter focus and CD budgets. [3,4] These improvements were embodied in the XLR 600ix and have been used in high volume manufacturing at 28, 20 and 14nm nodes, with a population exceeding 200 units worldwide [5]. To support reductions in critical dimension, the semiconductor roadmap demands further improvements in scanner resolution and throughput, which in turn places requirements on the light source for tighter optical performance and beam stability in a reduced exposure window, while operational cost pressures demand increases in efficiency and running costs. These drivers have led to improvements that have been implemented in Cymer's newest ring-architecture light source, the XLR 700ix.

2. IMPROVED CD CONTROL THROUGH HIGH BANDWIDTH STABILITY

Recent studies have shown that light source bandwidth variability can lead to measurable variations in CD uniformity within a wafer and wafer-to-wafer. While not all pattern types are sensitive to these variations both simulations and on-wafer measurements have demonstrated that isolated and semi-isolated patterns are more susceptible to bandwidth stability, as well as 'hot spots', or areas with low patterning margin. The example below

shows the results of a test on 14nm node contact holes with varying bandwidth resulting in a change to the contact hole CD dimensions.

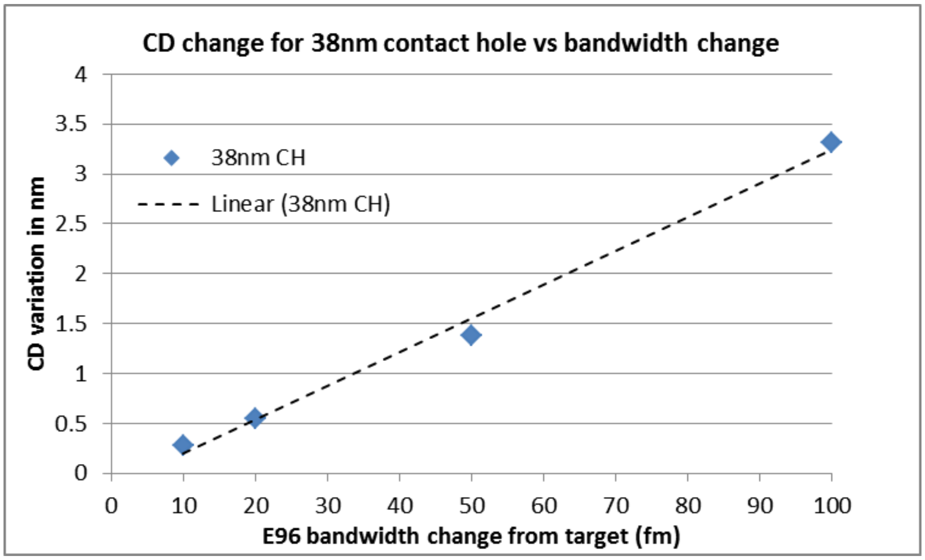

Figure 1 - 38nm nominal contact hole (14nm node) exposed with increasing bandwidth from a nominal 300fm E95 target.

This result suggests that light source bandwidth variation should be as minimal as possible, to avoid negatively impacting the process window and focus budget. To this end, light source bandwidth control technologies have been developed using proprietary, high speed, closed loop control to achieve extremely stable bandwidth, which has been incorporated in the XLR 700ix. While other techniques for bandwidth control involve mechanical actuation of optical elements, our patented technique here takes advantage of the dual-chamber, ring architecture where the chamber firing triggers are modulated to amplify a narrow part of the spectrum, resulting in an electronic (very fast) method to control bandwidth based on direct, in-situ bandwidth metrology. This technology enables the ability to meet E95 bandwidth specifications of 300±5fm wafer-to-wafer performance, ensuring that light source bandwidth performance has negligible impact on any on-wafer CD uniformity results.

3. GAS MANAGEMENT FUNCTIONS FOR HIGH EFFICIENCY

Excimer light sources require active gas management in the discharge chamber to ensure optimal performance using the prescribed concentrations of active species and operating pressures. Typical functions include frequent gas injects to compensate for fluorine species that are consumed during the discharge, as well as gas bleeds to minimize the buildup of by-products before they impact operating performance negatively. Optimum concentrations of active species need to change over time to compensate for system efficiency losses (e.g. due to optics degradation or discharge chamber aging). While this was historically managed through periodic service events (at the cost of system down time), an automated gas optimization (AGO) algorithm was introduced recently to periodically adjust the gas mix for maximum master oscillator (MO) chamber efficiency as well as bandwidth performance and bandwidth controller actuation range. This technology has been incorporated in the XLR 700ix in tandem with the fast bandwidth controller to ensure extremely stable bandwidth stability between major service events. The AGO algorithm leverages the periodic gas refill event to refill the chambers with an optimized gas mix and pressure, as illustrated in Figure 2 below. As a result, the system is able to maintain all the performance requirements, including bandwidth stability without loss of efficiency over time.

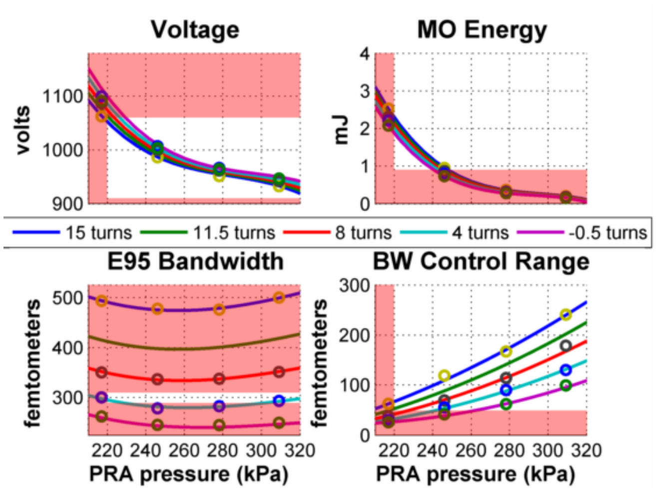

Figure 2 - AGO algorithm optimizes gas conditions to meet several variables simultaneously (chamber voltage, MO chamber energy, E95 bandwidth and bandwidth actuation range).

4. SYSTEM OPERATING COST IMPROVEMENTS

4.1 Electrical power consumption

There has been a constant drive to reduce the operating costs of leading-edge ArF immersion light sources, with opportunities explored around facilities costs (gas and electricity usage in particular). In the area of electricity usage, Cymer light sources have a history of providing increasing levels of output power without increasing the electrical consumption ("wall plug power"), through efficiency improvements that deliver more photons from the same discharge. The choice of a ring architecture has been particularly beneficial in this area, where the 'seed' beam from the MO chamber is amplified through multiple passes in the ring cavity, resulting in the ability to extract more power through system optimization. Figure **3**below illustrates this trend over multiple generations of light sources. More recently, advancement in chamber design has resulted in lower discharge operating voltages on average, which contribute to an overall reduction in input power consumption for the same level of output power. This chamber design has been field tested across more than 200 fielded systems, showing a consistent performance as illustrated in Figure **4**. This latest generation chamber is found in the XLR 700ix, providing another 15% improvement in electrical efficiency and reduction in power consumption.

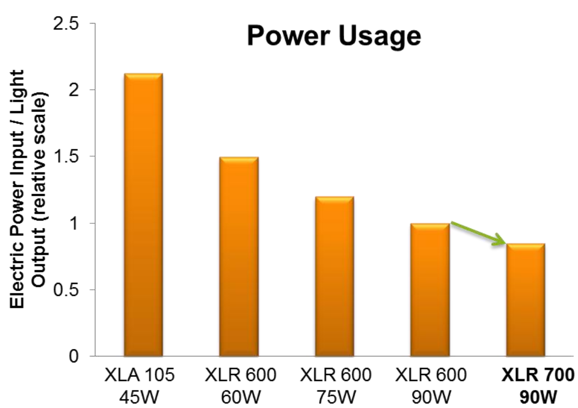

Figure 3 - Historical trend of higher efficiency light sources for successive generations, showing normalized output power vs. input electrical power.

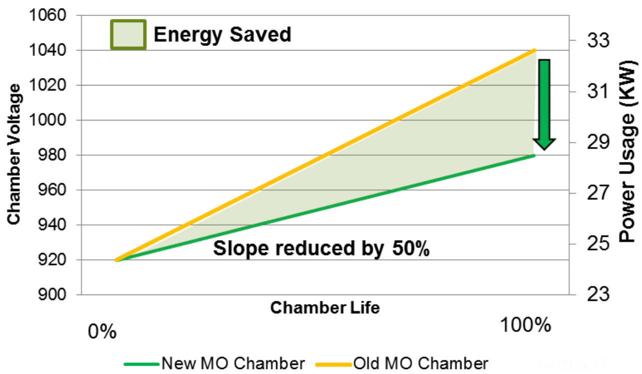

Figure 4 - Master oscillator (MO) chamber voltage over time, old design (orange) vs. new design (green).

4.2 Helium gas usage

Another opportunity in addressing operating costs is in the use of helium, which is used as a purge gas in the line narrowing module (LNM). While all other optical elements in the light source are purged using nitrogen, helium is used in the LNM due to its low change in index of refraction as a function of temperature (*dn/dT*). This is a factor of 40 lower than nitrogen and provides a very stable environment in the module responsible for delivering stable wavelength and bandwidth performance. As the optics in the LNM heat up with usage, their boundary layer also experiences fluctuations in temperature (as light source duty cycle is modulated with use). If nitrogen were used instead of helium, changes in duty cycle would result in index of refraction fluctuations near the optics, causing fluctuations in wavelength and bandwidth stability.

Concerns, however, about the price of helium and geopolitical influences on the continued supply have many semiconductor manufacturers looking for reduced dependence on helium. The opportunity for cost reduction for the light source is in the form of reduced helium flow rates, where detailed studies have shown that the system design improvements over time [7] allow a 50% in helium flow with negligible impact on system performance, and in particular bandwidth stability across the extremes of required duty cycle (Figure 5). While others have tried to eliminate helium altogether, they have done so at the cost of a more limited operating range for the light source to avoid bandwidth performance degradation (limitations on duty cycle, in particular) [6]. This reduced helium flow is also incorporated in the XLR 700ix, providing an approximate $3000 - $7000 reduction in annual helium costs per light source (depending on regional pricing).

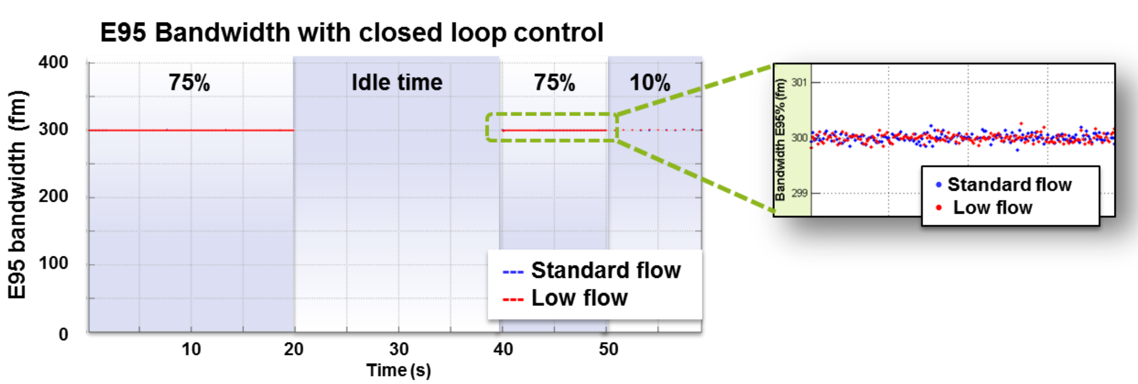

Figure 5 - E95 bandwidth performance with standard helium flow and 50% reduced (low) flow.

5. SUMMARY

To support the increasing performance and cost demands of ArF immersion multi-patterning, we have introduced technologies in the new XLR® 700ix light source that support on-wafer CD stability, while improving the system efficiency and operating costs. High-speed, closed-loop bandwidth control using electronic rather than optical actuators has enabled a very tight bandwidth stability of 300±5fm. Gas management algorithms have introduced automation (AGO) to maintain peak efficiency without service interventions. Helium gas consumption has been reduced by 50% without negatively impacting optical performance across all operating conditions. Lastly, leveraging the ring architecture design, we have demonstrated the continued increase in system efficiency, delivering the same power output (90W) for 15% lower electrical power over the previous model, following a >8 year trend in platform improvements over time.

6. REFERENCES

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